

A Model of the IEEE 802.11 DCF in Presence of Non Ideal Transmission Channel and Capture Effects

F. Daneshgaran, M. Laddomada, F. Mesiti, and M. Mondin

Abstract—In this paper, we provide a throughput analysis of the IEEE 802.11 protocol at the data link layer in non-saturated traffic conditions taking into account the impact of both transmission channel and capture effects in Rayleigh fading environment. Impacts of both non-ideal channel and capture become important in terms of the actual observed throughput in typical network conditions whereby traffic is mainly unsaturated, specially in an environment of high interference.

We extend the multi-dimensional Markovian state transition model characterizing the behavior at the MAC layer by including transmission states that account for packet transmission failures due to errors caused by propagation through the channel, along with a state characterizing the system when there are no packets to be transmitted in the buffer of a station.

Index Terms—Capture, DCF, Distributed Coordination Function, fading, IEEE 802.11, MAC, Rayleigh, rate adaptation, saturation, throughput, unsaturated, non-saturated.

I. INTRODUCTION

Wireless Local Area Networks (WLANs) using the IEEE802.11 series of standards have experienced an exponential growth in the recent past [1]-[13]. The Medium Access Control (MAC) layer of many wireless protocols resemble that of IEEE802.11. Hence, while we focus on this protocol, it is evident that the results easily extend to other protocols with similar MAC layer operation.

The most relevant works to what is presented here are [3], [4]. In [3] the author provided an analysis of the saturation throughput of the basic 802.11 protocol assuming a two dimensional Markov model at the MAC layer, while in [4] the authors extended the underlying model in order to consider unsaturated traffic conditions by introducing a new idle state, not present in the original Bianchi's model, accounting for the case in which the station buffer is empty, after a successful completion of a packet transmission. In the modified model, however, a packet is discarded after m backoff stages, while in the Bianchi's model, the station keeps iterating in the m -th backoff stage until the packet gets successfully transmitted.

In [5], the authors look at the impact of channel induced errors and the received SNR on the achievable throughput in a system with rate adaptation whereby the transmission rate of the terminal is adapted based on either direct or indirect

measurements of the link quality. In [6], the authors deal with the extension of Bianchi's Markov model in order to account for channel errors. Paper [7] proposes an extension of the Bianchi's model considering a new state for each backoff stage accounting for the absence of new packets to be transmitted, i.e., in unloaded traffic conditions.

In real networks, traffic is mostly unsaturated, so it is important to derive a model accounting for practical network operations. In this paper [2], we extend the previous works on the subject by looking at all the three issues outlined before together, namely real channel conditions, unsaturated traffic, and capture effects. Our assumptions are essentially similar to those of Bianchi [3] with the exception that we do assume the presence of both channel induced errors and capture effects due to the transmission over Rayleigh fading channel.

The paper is organized as follows. Section II extends the Markov model initially proposed by Bianchi, presenting modifications that account for transmission errors and capture effects over Rayleigh fading channels employing the 2-way handshaking technique in unsaturated traffic conditions. Section III provides an expression for the unsaturated throughput of the link. In section IV we present simulation results where typical MAC layer parameters for IEEE802.11b are used to obtain throughput values as a function of various system level parameters, capture probability, and SNR under typical traffic conditions. Finally, Section V is devoted to conclusions.

II. DEVELOPMENT OF THE MARKOV MODEL

In [3], an analytical model is presented for the computation of the throughput of a WLAN using the IEEE 802.11 DCF under ideal channel conditions. By virtue of the strategy employed for reducing the collision probability of the packets transmitted from the stations attempting to access the channel simultaneously, a random process $b(t)$ is used to represent the backoff counter of a given station. Backoff counter is decremented at the start of every idle backoff slot and when it reaches zero, the station transmits and a new value for $b(t)$ is set.

The value of $b(t)$ after each transmission depends on the size of the contention window from which it is drawn. Therefore it depends on the stations transmission history, rendering it a non-Markovian process. To overcome this problem and get to the definition of a Markovian process, a second process $s(t)$ is defined representing the size of the contention window from which $b(t)$ is drawn, ($W_i = 2^i W$, $i = s(t)$).

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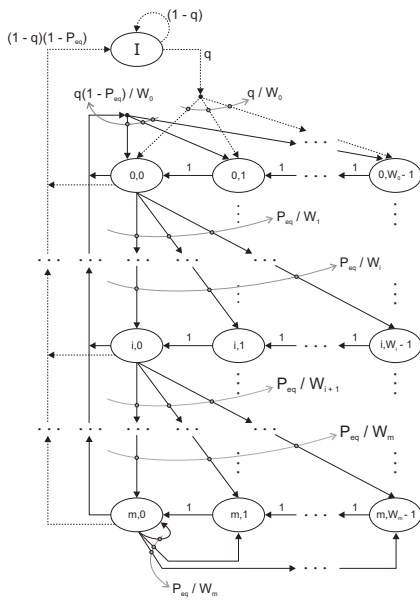


Fig. 1. Markov chain for the contention model in unsaturated traffic conditions, based on the 2-way handshaking technique, considering the effects of capture and channel induced errors.

A two-dimensional Markov process $(s(t), b(t))$ can now be defined, based on two assertions:

- 1) the probability τ that a station will attempt transmission in a generic time slot is constant across all time slots;
- 2) the probability P_{col} that any transmission experiences a collision is constant and independent of the number of collisions already suffered.

The main aim of this section is to propose an effective modification of the bi-dimensional Markov process proposed in [3] in order to account for unsaturated traffic conditions, channel error propagation and capture effects over a Rayleigh fading channel under the hypothesis of employing a 2-way handshaking access mechanism.

On the basis of this assumption, collisions can occur with probability P_{col} on the transmitted packets, while transmission errors due to the channel, can occur with probability P_e . We assume that collisions and transmission error events are statistically independent. In this scenario, a packet is successfully transmitted if there is no collision (this event has probability $1 - P_{col}$) and the packet encounters no channel errors during transmission (this event has probability $1 - P_e$). The probability of successful transmission is therefore equal to $(1 - P_e)(1 - P_{col})$, from which we can set an equivalent probability of failed transmission as $P_{eq} = P_e + P_{col} - P_e P_{col}$.

Furthermore, in mobile radio environment, it may happen that the channel is captured by a station whose power level is stronger than other stations transmitting at the same time. This may be due to relative distances and/or channel conditions for each user and may happen whether or not the terminals exercise power control. Capture effect often reduces the collision probability on the channel since the stations whose power level at the receiver are very low due to path attenuation, shadowing and fading, are considered as interferers at the AP raising the noise floor.

To simplify the analysis, we make the assumption that the impact of the channel induced errors on the RTS, CTS and Acknowledgment (ACK) packets are negligible because of their short length. This is justified on the basis of the assumption that the bit errors inflicting the transmitted data are independent of each other. We note that with sufficient interleaving we can always ensure that the errors inflicting individual bits in a data packet are independent of each other [14], [17].

Practical networks operate in unsaturated traffic conditions. In this case, Bianchi's model [3] assuming the presence of a packet to be transmitted in each and every station's buffer, is not valid anymore. However, the simplicity of such a model can be retained also in unsaturated conditions by introducing a new state, labelled I , accounting for the following two situations:

- immediately after a successful transmission, the buffer of the transmitting station is empty;
- the station is in an idle state with an empty buffer until a new packet arrives at the buffer for transmission.

With these considerations in mind, let us discuss the Markov model shown in Fig. 1, modelling unsaturated traffic condition. The Markov Process of Fig. 1 is governed by the following transition probabilities¹:

$$\begin{aligned}
 P_{i,k|i,k+1} &= 1, & k \in [0, W_i - 2], i \in [0, m] \\
 P_{0,k|i,0} &= q(1 - P_{eq})/W_0, & k \in [0, W_0 - 1], i \in [0, m] \\
 P_{i,k|i-1,0} &= P_{eq}/W_i, & k \in [0, W_i - 1], i \in [1, m] \\
 P_{m,k|m,0} &= P_{eq}/W_m, & k \in [0, W_m - 1] \\
 P_{I|i,0} &= (1 - q)(1 - P_{eq}), & i \in [0, m] \\
 P_{0,k|I} &= q/W_0, & k \in [0, W_0 - 1] \\
 P_{I|I} &= 1 - q
 \end{aligned} \tag{1}$$

The first equation in (1) states that, at the beginning of each slot time, the backoff time is decremented. The second equation accounts for the fact that after a successful transmission, a new packet transmission starts with backoff stage 0 with probability q , in case there is a new packet in the buffer to be transmitted. Third and fourth equations deal with unsuccessful transmissions and the need to reschedule a new contention stage. The fifth equation deals with the practical situation in which after a successful transmission, the buffer of the station is empty, and as a consequence, the station transits in the idle state I waiting for a new packet arrival. The sixth equation models the situation in which a new packet arrives in the station buffer, and a new backoff procedure is scheduled. Finally, the seventh equation models the situation in which there are no packets to be transmitted and the station is in the idle state.

III. MARKOVIAN PROCESS ANALYSIS AND THROUGHPUT COMPUTATION

Next line of pursuit consists in finding a solution of the stationary distribution:

$$b_{i,k} = \lim_{t \rightarrow \infty} P[s(t) = i, b(t) = k], \forall k \in [0, W_i - 1], \forall i \in [0, m]$$

¹ $P_{i,k|j,n}$ is short for $P\{s(t+1) = i, b(t+1) = k | s(t) = j, b(t) = n\}$.

that is, the probability of a station occupying a given state at any discrete time slot. First, we note the following relations:

$$\begin{aligned} b_{i,0} &= P_{eq} \cdot b_{i-1,0} = P_{eq}^i \cdot b_{0,0}, \quad \forall i \in [1, m-1] \\ b_{m,0} &= \frac{P_{eq}^m}{1-P_{eq}} \cdot b_{0,0}, \quad i = m \end{aligned} \quad (2)$$

whereby P_{eq} is the equivalent probability of failed transmission, that takes into account the need for a new contention due to either packet collision (P_{col}) or channel errors (P_e), i.e., $P_{eq} = P_{col} + P_e - P_e \cdot P_{col}$.

State b_I in Fig. 1 considers both the situation in which after a successful transmission there are no packets to be transmitted, and the situation in which the packet queue is empty and the station is waiting for new packet arrival. The stationary probability to be in state b_I can be evaluated as follows:

$$\begin{aligned} b_I &= (1-q)(1-P_{eq}) \cdot \sum_{i=0}^m b_{i,0} + (1-q) \cdot b_I \\ &= \frac{(1-q)(1-P_{eq})}{q} \cdot \sum_{i=0}^m b_{i,0} \end{aligned} \quad (3)$$

The expression above reflects the fact that state b_I can be reached after a successful packet transmission from any state $b_{i,0}$, $\forall i \in [0, m]$ with probability $(1-q)(1-P_{eq})$, or because the station is waiting in idle state with probability $(1-q)$, whereby q is the probability of having at least one packet to be transmitted in the buffer. The statistical model of q will be discussed in the next section.

The other stationary probabilities for any $k \in [1, W_i - 1]$ follow by resorting to the state transition diagram shown in Fig. 1:

$$b_{i,k} = \frac{W_i - k}{W_i} \begin{cases} q(1-P_{eq}) \cdot \sum_{i=0}^m b_{i,0} + q \cdot b_I, & i = 0 \\ P_{eq} \cdot b_{i-1,0}, & i \in [1, m-1] \\ P_{eq}(b_{m-1,0} + b_{m,0}), & i = m \end{cases} \quad (4)$$

Employing the normalization condition, after lengthy algebra, and remembering the relation $\sum_{i=0}^m b_{i,0} = \frac{b_{0,0}}{1-P_{eq}}$, it is possible to obtain:

$$1 = \frac{b_{0,0}}{2} \left[W \left(\sum_{i=0}^{m-1} (2P_{eq})^i + \frac{(2P_{eq})^m}{1-P_{eq}} \right) + \frac{1}{1-P_{eq}} + \frac{2(1-q)}{q} \right] \quad (5)$$

Normalization condition yields the following equation for computation of $b_{0,0}$:

$$\frac{2(1-P_{eq})(1-2P_{eq})q}{q[(W+1)(1-2P_{eq}) + WP_{eq}(1-(2P_{eq})^m)] + 2(1-q)(1-P_{eq})(1-2P_{eq})} \quad (6)$$

Equ. (6) is then used to compute τ , the probability that a station starts a transmission in a randomly chosen time slot:

$$\tau = \frac{2(1-2P_{eq})q}{q[(W+1)(1-2P_{eq}) + WP_{eq}(1-(2P_{eq})^m)] + 2(1-q)(1-P_{eq})(1-2P_{eq})} \quad (7)$$

The collision probability needed to compute τ can be found considering that using a 2-way hand-shaking mechanism, a packet from a transmitting station encounters a collision if in a given time slot, at least one of the remaining $(N-1)$ stations transmits simultaneously another packet, and there is no capture. In our model, we assume that capture is a subset of the collision events. This is indeed justified by the fact that there is no capture without collision, and that capture occurs only because of collisions between a certain number

of transmitting stations attempting to transmit simultaneously on the channel.

$$P_{col} = 1 - (1-\tau)^{N-1} - P_{cap} \quad (8)$$

As far as the capture effects are concerned, we resort to the mathematical formulation proposed in [9], [10]. In particular, under the hypothesis of power-controlled stations in infrastructure mode, the capture probability conditioned on i interfering frames can be defined as follows:

$$P_{cp}(\gamma > z_0 g(S_f) | i) = \frac{1}{[1 + z_0 g(S_f)]^i} \quad (9)$$

whereby, γ , defined as $P_u / \sum_{k=1}^i P_k$, is the ratio of the power P_u of the useful signal and the sum of the powers of the i interfering channel contenders transmitting simultaneously i frames, $g(S_f)$ is the inverse of the processing gain of the correlation receiver, and z_0 is the capture ratio, i.e., the value of the signal-to-interference power ratio identifying the capture threshold at the receiver. Notice that (9) signifies the fact that capture probability corresponds to the probability that the power ratio γ is above the capture threshold $z_0 g(S_f)$ which considers the inverse of the processing gain $g(S_f)$. For Direct Sequence Spread Spectrum (DSSS) using a 11-chip spreading factor ($S_f = 11$), we have $g(S_f) = \frac{2}{3S_f}$.

Upon defining the probability of generating exactly $i+1$ interfering frames over N contending stations in a generic slot time:

$$\binom{N}{i+1} \tau^{i+1} (1-\tau)^{N-i-1}$$

the frame capture probability P_{cap} can be obtained as follows:

$$P_{cap} = \sum_{i=1}^{N-1} \binom{N}{i+1} \tau^{i+1} (1-\tau)^{N-i-1} P_{cp}(\gamma > z_0 g(S_f) | i) \quad (10)$$

Putting together Equ.s (7), (8), and (10), along with P_{eq} , the following nonlinear system can be defined and solved numerically, obtaining the values of τ , P_{col} , P_{cap} , and P_{eq} :

$$\begin{cases} \tau = \frac{2(1-2P_{eq})q}{q[(W+1)(1-2P_{eq}) + WP_{eq}(1-(2P_{eq})^m)] + 2(1-q)(1-P_{eq})(1-2P_{eq})} \\ P_{col} = 1 - (1-\tau)^{N-1} - P_{cap} \\ P_{eq} = P_{col} + P_e - P_e \cdot P_{col} \\ P_{cap} = \sum_{i=1}^{N-1} \binom{N}{i+1} \tau^{i+1} (1-\tau)^{N-i-1} \frac{1}{(1+z_0 g(S_f))^i} \end{cases} \quad (11)$$

The final step in the analysis is the computation of the normalized system throughput, defined as the fraction of time the channel is used to successfully transmit payload bits:

$$S = \frac{P_t \cdot P_s \cdot (1-P_e) E[PL]}{(1-P_t)\sigma + P_t(1-P_s)T_c + P_t P_s(1-P_e)T_s + P_t P_s P_e T_e} \quad (12)$$

where the meaning of the underlined symbols is as follows.

P_t is the probability that there is at least one transmission in the considered time slot, with N stations contending for the channel, each transmitting with probability τ :

$$P_t = 1 - (1-\tau)^N \quad (13)$$

P_s is the conditional probability that a packet transmission occurring on the channel is successful. This event corresponds

TABLE I
TYPICAL NETWORK PARAMETERS

MAC header	24 bytes	τ_p	1 μ s
PHY header	16 bytes	Slot time	20 μ s
Payload size, E[PL]	1024 bytes	SIFS	10 μ s
ACK	14 bytes	DIFS	50 μ s
RTS	20 bytes	EIFS	300 μ s
CTS	14 bytes	ACK,CTS timeout	300 μ s
m	5	W	32
T_s	8.812 ms	T_c	8.812 ms

to the case in which exactly one station transmits in a given time slot, or two or more stations transmit simultaneously and capture by the desired station occurs. These conditions yields the following probability:

$$P_s = \frac{N\tau(1-\tau)^{N-1} + P_{cap}}{P_t} \quad (14)$$

T_c , T_e and T_s are the average times a channel is sensed busy due to a collision, error affected data frame transmission time and successful data frame transmission times, respectively. Knowing the time durations for ACK frames, ACK timeout, DIFS, SIFS, σ , data packet length (PL) and PHY and MAC headers duration (H), and propagation delay τ_p , T_c , T_s , and T_e can be computed as suggested in [11]. $E[PL]$ is the average packet payload length. σ is the duration of an empty time slot.

A. Modelling offered load and estimation of probability q

In our analysis, the offered load related to each station is characterized by parameter λ representing the rate at which packets arrive at the station buffer from the upper layers, and measured in pkt/s . The time between two packet arrivals is defined as *interarrival time*, and its mean value is evaluated as $\frac{1}{\lambda}$. One of the most commonly used traffic models assumes packet arrival process is Poisson. The resulting interarrival times are exponentially distributed.

In the proposed model, we need a probability, identified by q , that indicates if at the end of a given transmission there is at least one packet in the queue to be transmitted. Probability q can be well approximated in a situation with small buffer size [13] through the following relation:

$$q = 1 - e^{-\lambda E[S_{ts}]} \quad (15)$$

where, $E[S_{ts}]$ is the *expected time per slot*, which is useful to relate the state of the Markov chain with the actual time spent in each state.

A more accurate model can be derived upon considering different values of q for each backoff state. However, a reasonable solution consists in using a mean probability valid for the whole Markov model [13], derived from $E[S_{ts}]$. The value of $E[S_{ts}]$ can be obtained by resorting to the durations and the respective probabilities of the idle slot (σ), the successful transmission slot (T_s), the error slot due to collision (T_c), and the error slot due to channel (T_e), as follows:

$$E[S_{ts}] = (1 - P_t) \cdot \sigma + P_t(1 - P_s) \cdot T_c + P_t P_s P_e \cdot T_e + P_t P_s (1 - P_e) \cdot T_s \quad (16)$$

Upon recalling that packet inter-arrival times are exponentially distributed, we can use the average slot time to calculate the probability q that in such a time interval a given station receives a packet from upper layers in its transmission queue. The probability that in a generic time T , k events occur, is:

$$P\{a(T) = k\} = e^{-\lambda T} \frac{(\lambda T)^k}{k!} \quad (17)$$

from which we obtain the relation (15) referred to earlier:

$$q = 1 - P\{a(E[S_{ts}]) = 0\} = 1 - e^{-\lambda E[S_{ts}]} \quad (18)$$

IV. SIMULATION RESULTS AND MODEL VALIDATIONS

This section focuses on simulation results for validating the theoretical models and derivations presented in the previous sections. We have developed a C++ simulator modelling both the DCF protocol details in 802.11b and the backoff procedures of a specific number of independent transmitting stations. The simulator also takes into account all real operations of each transmitting station, including physical propagation delays, etc.

Typical MAC layer parameters for the lowest rate IEEE802.11b are given in Table I [1]. In so far as the computation of the FER is concerned, it should be noted that data transmission rate of various packet types differ. For simplicity, we assume that data packets transmitted by different stations are affected by the same FER.

The FER as a function of the SNR can be computed as follows:

$$P_e(SNR) = 1 - [1 - P_e(PLCP, SNR)] \cdot [1 - P_e(DATA, SNR)] \quad (19)$$

where,

$$P_e(PLCP, SNR) = 1 - [1 - P_b(BPSK, SNR)]^{8 \times PLCP}, \quad (20)$$

and

$$P_e(DATA, SNR) = 1 - [1 - P_b(TYPE, SNR)]^{8 \times (DATA + MAC)}. \quad (21)$$

$P_b(BPSK, SNR)$ is the BER as a function of SNR for the lowest data transmit rate employing DBPSK modulation, DATA denotes the data block size in bytes, and any other constant byte size in above expression represents overhead. Note that the FER, $P_e(SNR)$, implicitly depends on the modulation format used. Hence, for each supported rate, one curve for $P_e(SNR)$ as a function of SNR can be generated. $P_b(TYPE, SNR)$ is modulation dependent whereby the parameter TYPE can be any of the following $TYPE \in \{DBPSK, DQPSK, CCK5.5, CCK11\}^2$.

For DBPSK and DQPSK modulation formats, $P_b(TYPE, SNR)$ can be well approximated by [18]:

$$\frac{2}{\max(\log_2 M, 2)} \sum_{i=1}^{\max(\frac{M}{4}, 1)} \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \frac{1}{1 + \gamma \frac{1}{\sin^2 \theta} \log_2 M \sin^2 \left(\frac{(2i-1)\pi}{M} \right)} d\theta \quad (22)$$

whereby M is the number of bits per modulated symbols, γ is the signal-to-noise ratio, and θ is the signal direction over the Rayleigh fading channel.

²The acronyms are short for Differential Binary Phase Shift Keying, Differential Quadrature Phase Shift Keying and Complementary Code Keying, respectively.

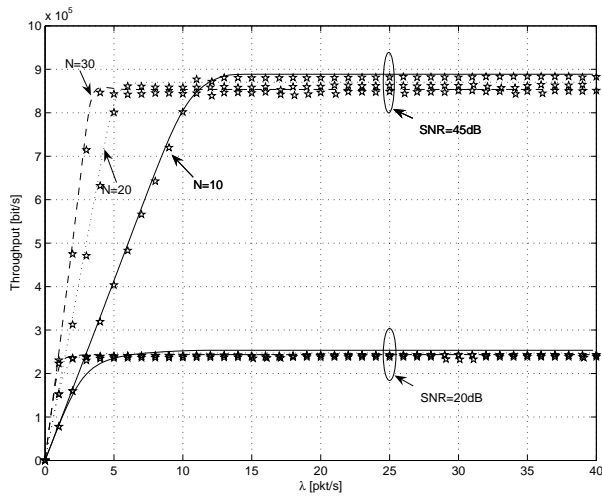


Fig. 2. Theoretical and simulated throughput for the 2-way mechanism as a function of the packet rate λ , for three different number of contending stations and two different values of SNR as noted in the legend. Capture thresholds is $z_0 = 6\text{dB}$. Simulated points are identified by star-markers over the respective theoretical curves. Payload size is 1024 bytes.

Fig. 2 shows the behavior of the throughput as a function of λ , i.e., the packet rate, for three different values of the number of contending stations and for two values of SNR. The capture threshold is $z_0 = 6\text{dB}$. Beside noting the throughput improvement achievable for high SNR, notice that for a specified number of contending stations, the throughput manifests a linear behaviour for low values of packet rates with a slope depending mainly on the number of stations N . However, for increasing values of λ , the saturation behavior occurs quite fast. Notice that, as exemplified in (18), $q \rightarrow 1$ as $\lambda \rightarrow \infty$. Actually, saturated traffic conditions are achieved quite fast for values of λ on the order of ten packets per second with a number of contending stations greater than or equal to 10.

Fig. 3 shows the behavior of the throughput as a function of λ , for three different values of the number of contending stations and for two different SNRs. The capture threshold is $z_0 = 24\text{dB}$. We can draw conclusions similar to the ones derived for Fig. 2. Upon comparing the curves shown in Figs 2 and 3, it is easily seen that capture effects allow the system throughput to be almost the same independently from the number of stations in saturated conditions, i.e., for high values of λ .

Fig. 3 also shows the presence of a peak in the throughput as a function of λ , which characterizes the transition between the linear and saturated throughput. Such a peak tends to manifest itself for increasing values of λ as the number of stations N decreases. A comparative analysis of the curves shown in Figs 2 and 3 reveals that the peak of the throughput tends to disappear because of the presence of capture effects during transmission.

V. CONCLUSIONS

In this paper, we have provided an extension of the Markov model characterizing the DCF behavior at the MAC layer of the IEEE802.11 series of standards by accounting for channel

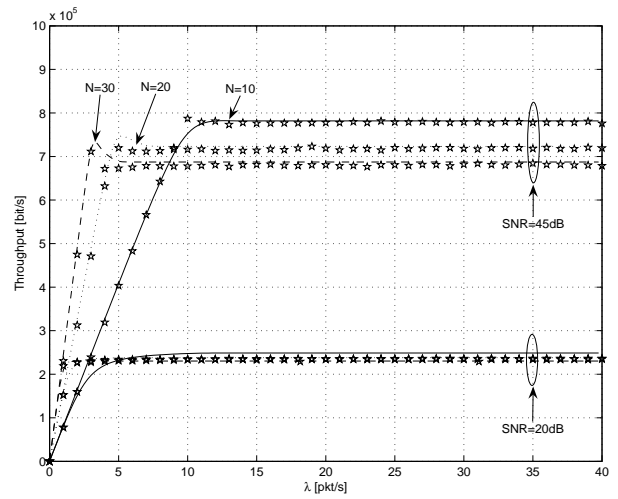


Fig. 3. Theoretical and simulated throughput for the 2-way mechanism as a function of the packet rate λ , for three different number of contending stations and two different values of SNR as noted in the legend. Capture threshold is $z_0 = 24\text{dB}$. Simulated points are identified by star-markers over the respective theoretical curves. Payload size is 1024 bytes.

induced errors and capture effects typical of fading environments under unsaturated traffic conditions. The modelling allows taking into consideration the impact of channel contention in throughput analysis which is often not considered or it is considered in a static mode by using a mean contention period. Simulation results confirm the validity of the proposed theoretical models.

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